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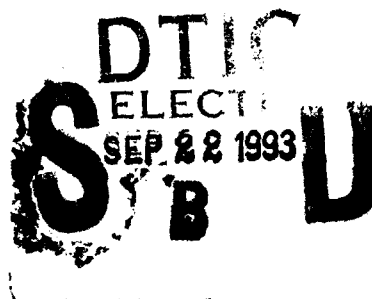


# Fabrication Process for Cantilever Beam Micromechanical Switches

by Timothy J. Mermagen and  
Bernard J. Rod

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13. ABSTRACT (Maximum 200 words)  This report presents a detailed process description for fabrication of a micromechanical accelerometer sensor switch. The switch consists of a metallic cantilever beam structure that is defined with silicon micromachining processing technology. The beam is made up of a gold-nickel-gold tri-metallic structure, which is anchored at one end to a silicon substrate; the process was designed to be compatible with current integrated circuit technology used in industry.				
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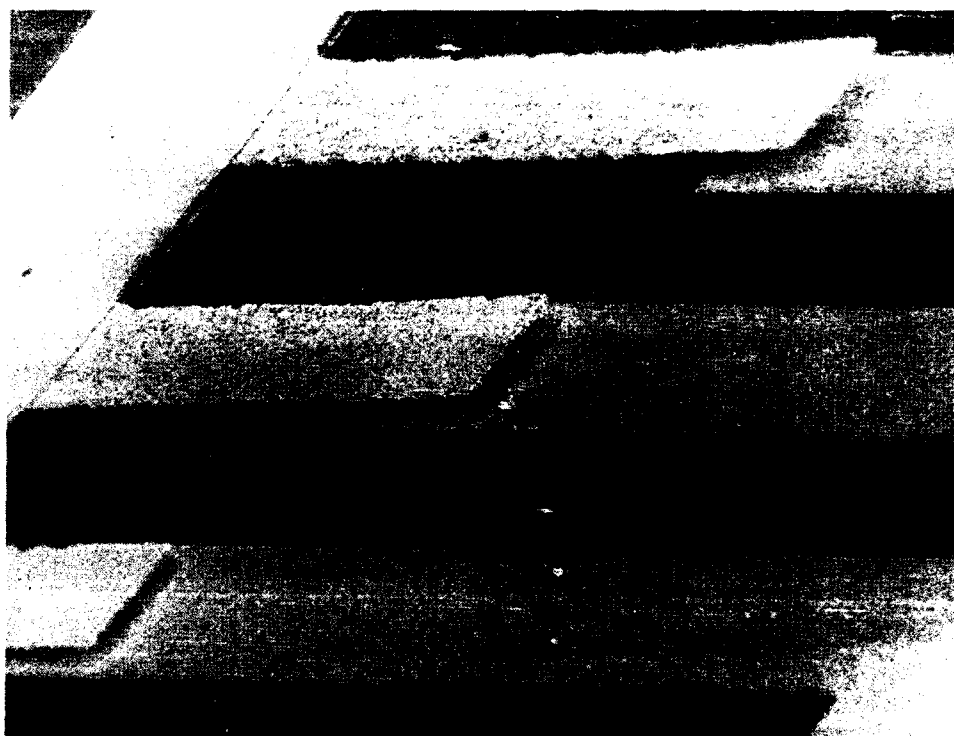
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# 1. Introduction

A process for fabricating advanced micromechanical sensors used in safety and arming devices, munitions, and electronic fuzes was designed at the Army Research Laboratory (ARL). The main objective of this program was to develop a process for the fabrication of cantilever beam mechanical switches on a silicon substrate that is compatible with standard integrated circuit manufacturing technology (app A).<sup>1,2</sup> The switch consists of a number of cantilever (diving-board-shaped) beams that are open in the up (relaxed) position and closed in the down (stressed) position. The switching mechanism was designed to close when a specific acceleration threshold was exceeded and to remain open or to reopen when below this threshold. Three cantilever beam sizes, for three different acceleration thresholds, were processed and tested. A comparison of this work with other designs was presented at Transducers '87.<sup>3</sup>

A photomicrograph of an actual device is shown in figure 1.

Figure 1. Three-beam device.



<sup>1</sup>L. I. Maissel and R. Glang, *Handbook of Thin Film Technology*, McGraw-Hill Book Co., New York (1970), pp 7-37.

<sup>2</sup>W. D. Frobenis, S. A. Zeitman, M. H. White, D. D. O'Sullivan, and R. G. Hamel, *Microminiature Ganged Threshold Accelerometers Compatible with Integrated Circuit Technology*, IEEE Trans. Electron Devices ED-19, No. 1 (January 1972).

<sup>3</sup>C. Robinson, D. Overman, R. Warner, and T. Blomquist, *Problems Encountered in the Development of a Microscale G-Switch Using Three Design Approaches*, Proceedings, 4th International Conference on Solid-State Sensors and Actuators, Transducers '87, pp 410-413.

## 2. Cantilever Beam Fabrication Process

The beam fabrication process incorporates four different photomasking levels with 62 processing steps (see list 1). These steps are combinations of materials deposition and etching techniques (app B) used to control the film uniformity, the beam lengths and thicknesses, and the final gap parameters between the metal contacts. The beam structure is a tri-metallic strip made up of a single layer of nickel sandwiched between two layers of gold. The nickel film was integrated into the beam structure as a means of enhancing the thermal and tensile characteristics of the beam during deflection.

The process begins with removal of all organic and metallic contaminants from a silicon substrate in a standard MOS (metal oxide semiconductor) cleaning process (app B). After adequate rinsing in deionized water, a 1000-Å layer of thermal oxide ( $\text{SiO}_2$ ) is grown (fig. 2a). This oxide acts as an insulation layer between the conduction pathways on the cantilever switch and the semiconductor silicon substrate. On top of this oxide, a 2000-Å layer of polysilicon is deposited by LPCVD (low-pressure chemical vapor deposition) (fig. 2b). This layer is used as an etch barrier to protect the lower  $\text{SiO}_2$  insulator during final patterning of the cantilever switch. The polysilicon layer makes a good etch barrier because of the selectivity of the polysilicon etch. After the electrical isolation layer and etch barrier are grown and deposited, the cantilever structure is fabricated.

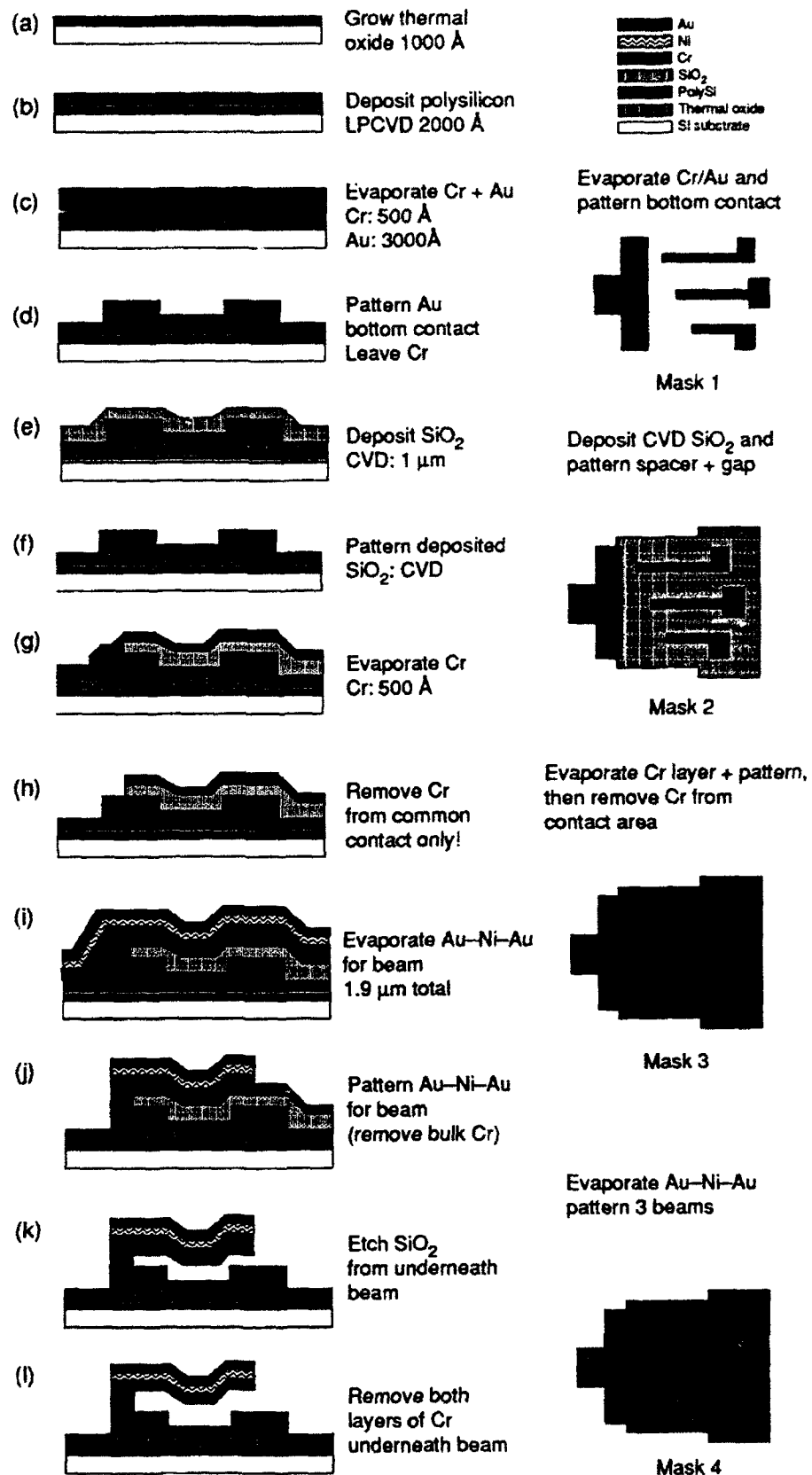
List 1. Steps in cantilever beam process.

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1. MOS clean wafer	21. Develop and rinse	44. De-scum in plasma etcher in $\text{O}_2$
2. Grow oxide to 1000 Å	22. De-scum in plasma etcher in $\text{O}_2$	45. Hard bake
3. Deposit polysilicon to 2000 Å (LPCVD)	23. Hard bake	46. Etch gold-nickel-gold, 70 s
4. Evaporate chrome to 500 Å	24. Etch $\text{SiO}_2$ in buffered HF	47. Hard bake 5 min.
5. Evaporate gold to 3000 Å	25. Plasma ash photoresist in $\text{O}_2$	48. Etch CVD $\text{SiO}_2$ buffered HF, 2.5 min.
6. Apply HMDS (hexamethyldisilazane)	26. Evaporate chrome to 500 Å	49. Plasma ash photoresist in $\text{O}_2$
7. Apply negative photoresist	27. Apply HMDS	50. Etch CVD $\text{SiO}_2$ buffered HF, 8 min.
8. Soft bake (90°C)	28. Apply negative photoresist	51. Etch both chrome layers, 3 min.
9. Expose mask level 1	29. Soft bake	52. Deionized (Di) $\text{H}_2\text{O}$ rinse, air dry
10. Develop and rinse	30. Expose mask level 2	53. Examine beams
11. De-scum in plasma etcher in $\text{O}_2$	31. Develop and rinse	54. Apply photoresist (secure beams)
12. Hard bake (134 to 140°C)	32. De-scum in plasma etcher in $\text{O}_2$	55. Soft bake
13. Etch gold, 45 s	33. Hard bake	56. Separate die (wafer saw)
14. Etch chrome, 30 s	34. Etch chrome, 45 s	57. $\text{DiH}_2\text{O}$ rinse, air dry
15. Plasma ash (etch) photoresist in $\text{O}_2$	35. Plasma ash photoresist in $\text{O}_2$	58. Plasma ash photoresist in $\text{O}_2$
16. Deposit $\text{SiO}_2$ to 10,000 Å (CVD)	36. Evaporate gold to 9000 Å	59. Die bond to header package (TO-5)
17. Apply HMDS	37. Evaporate nickel to 1000 Å	60. Bond die with gold wire
18. Apply negative photoresist	38. Evaporate gold to 9000 Å	61. Cap TO-5 header
19. Soft bake	39. Apply HMDS	62. Perform centrifuge testing
20. Expose mask level 2	40. Apply negative photoresist	
	41. Soft bake	
	42. Expose mask level 3	
	43. Develop and rinse	

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**Figure 2.**  
Diagrammatic  
fabrication steps.



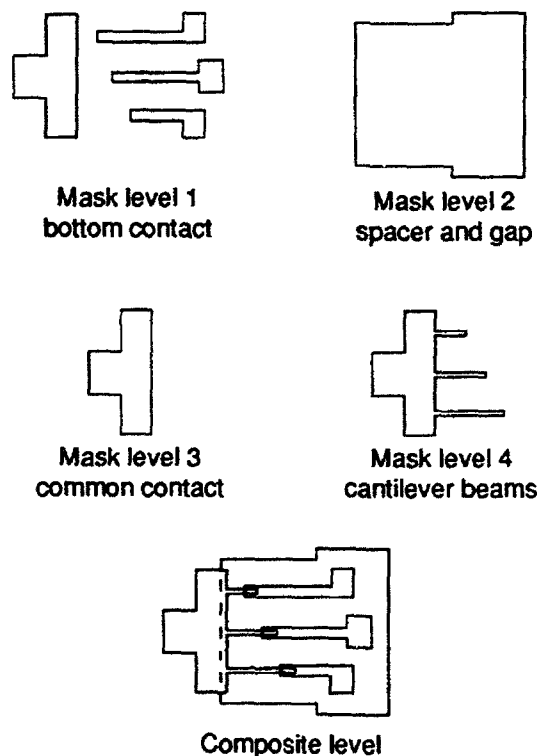
The cantilever switch consists of a beam structure that is anchored on one end and floats at a distance called the "beam gap" above a contact pad on the other end. The contact and anchor consist of 3000 Å of thermally evaporated gold, which sits atop 500 Å of thermally evaporated chrome (fig. 2c). The thin layer of chrome acts as a glue layer between the gold and the polysilicon. The gold and chrome layers are then patterned (fig. 2d) and etched with photomask 1 (fig. 3), which defines the beam anchor and contact on top of the polysilicon.

Upon the beam anchor and contact, a 10,000-Å layer of CVD (chemical vapor deposition) oxide is deposited to act as a spacer for the future beams (fig. 2e). This oxide defines the "beam gap" of the cantilever switch. The spacer oxide is patterned (fig. 2f) and etched with photomask 2 (fig. 3).

Deposited upon this spacer oxide is a sacrificial adhesion layer consisting of 500 Å of evaporated chrome (fig. 2g). This chrome layer is used as a glue layer for attaching the beam structure to the spacer oxide. The chrome is then patterned (fig. 2h) and etched with photomask 3 (fig. 3). The chrome is removed from on top of the anchor area to allow for a gold-to-gold adhesion (high-quality adhesion) of the beam to the anchor in subsequent steps.

The final metal depositions form the beam structure. This structure is built up on top of the patterned chrome. The beam is basically a tri-metallic strip made up of a 1.9-μm-thick, thermally evaporated gold-nickel-gold sandwich (fig. 2i). The center nickel layer adds rigidity to the beam structure. The bottom layer of gold gives the beam tri-metallic strip properties, allowing for uniform thermal expansion

**Figure 3. Photomask levels and composite.**





between the top and bottom surfaces of the beam. The beam structure is etched and patterned (fig. 2j) with photomask 4 (fig. 3).

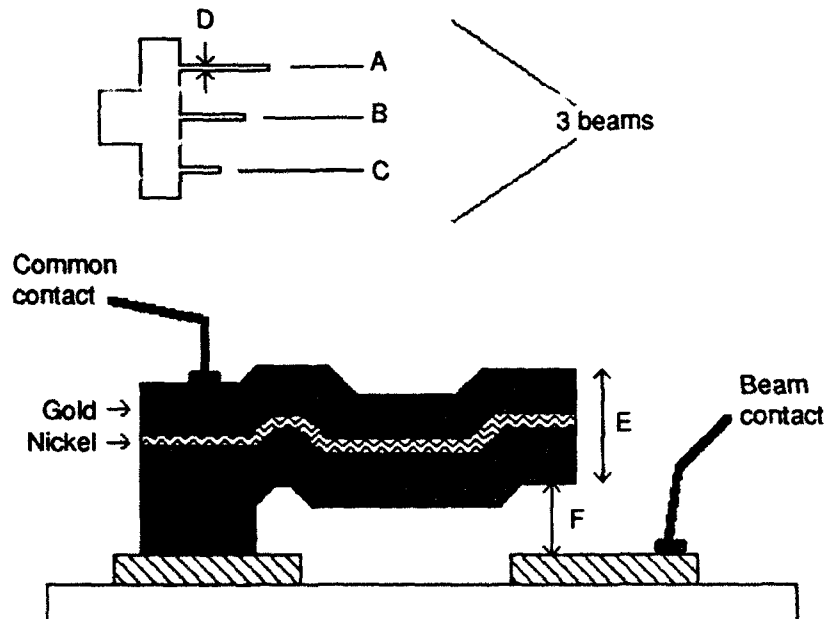
Once the beams have been defined, the spacer oxide is removed from underneath by a buffered HF etch solution (fig. 2k). The polysilicon layer protects the lower  $\text{SiO}_2$  layer on the bulk silicon substrate from being etched while the spacer oxide is being removed.

The chrome glue layer, under the beam and between the beam contact and anchor, is removed next (fig. 2l). This electrically isolates the beam from the contact. Once this final step is completed, the beams are finished and ready for dicing (individual die separation).

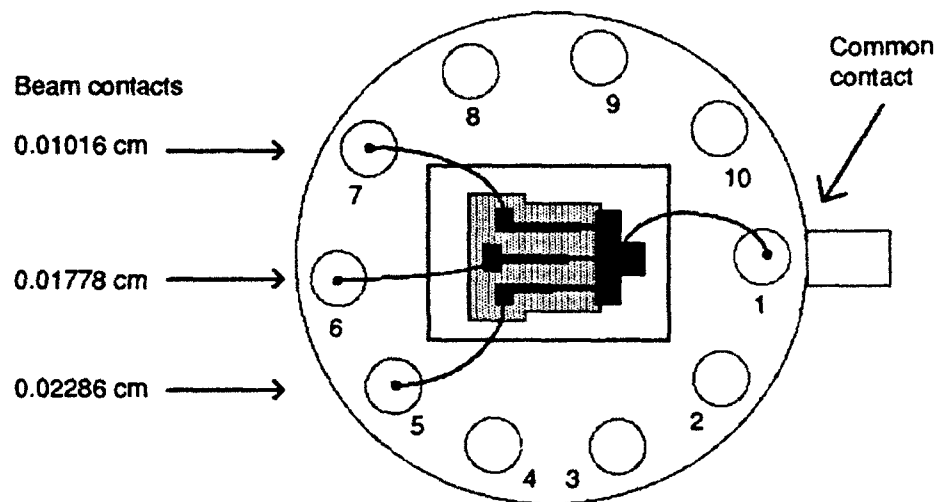
After the beams were fully processed, the individual beam structures, which consist of three different-length cantilever beams on one common anchor with three separate contacts (fig. 4), must be separated into single dies for packaging and testing. As a first step, the beams are stabilized with poured on (not spun on) photoresist; this supports the fragile, free-floating beams during the wafer dicing process. The photoresist is then soft baked  $\pm 90^\circ\text{C}$  for 30 minutes before die separation. The die separation at ARL was performed on a Micro Automation wafer dicing saw, which uses a water spray for cooling the saw blade and removing debris from the surface of the wafer. After separation, the photoresist is removed from the individual dies by plasma ashing and wet chemistry. The cantilever beam group dies are then individually mounted and bonded into a test package. ARL used a TO-5 header package (fig. 5) for the electrical and centrifugal testing, and the die were mounted on the header with epoxy (fig. 6).

Figure 4. Actual beam parameters.

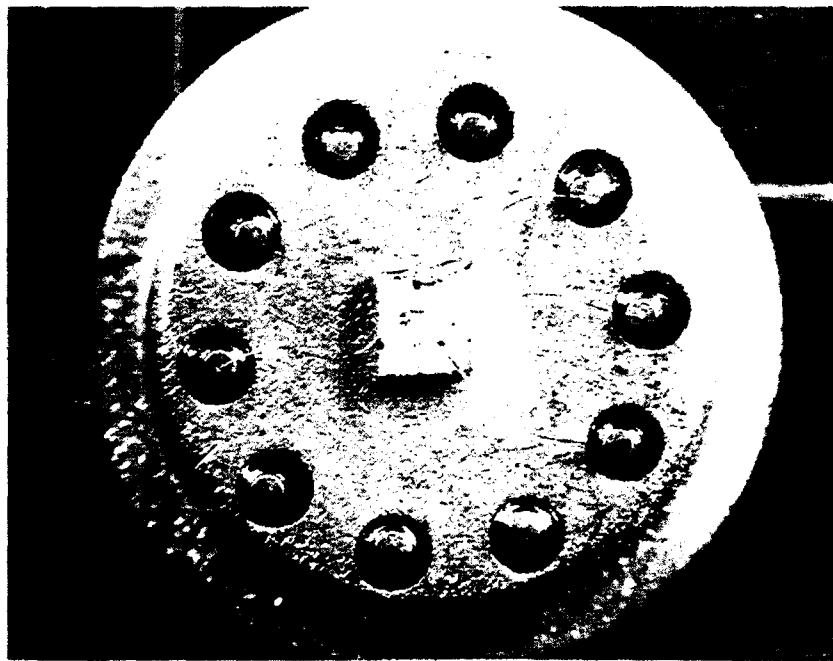
Beam lengths (3)	A: 228.6 $\mu\text{m}$
	B: 177.8 $\mu\text{m}$
	C: 101.6 $\mu\text{m}$
Beam width	D: 50.8 $\mu\text{m}$
Beam thickness	E: 1.9 $\mu\text{m}$
Beam spacer and contact gap	F: 1.0 $\mu\text{m}$



**Figure 5. Die contact (TO-5).**



**Figure 6. Photograph of TO-5 header with beams.**



### 3. Results and Problem Areas

The laboratory fabrication of the metal beam cantilever switches on 2-in.-diameter silicon substrates yielded more than 800 dies per wafer. The final yield of functioning cantilever switches was approximately 40 percent per wafer. This low yield is believed to be caused by imperfect fabrication techniques and stress-point failure.

After the wafer sawing procedure and the removal of the photoresist, a number of the cantilever beams were found to be broken off at the anchor point and others were bent or twisted; these problems were not evident before the photoresist was removed. We believe the deformities were caused by wafer handling that disclosed stress points at the root of the beams. We would need to investigate further

to see whether wafer handling can be minimized in such procedures as die separation and post-gap oxide removal processing. It should also be possible to alleviate the stress point at the root of the beam, which may be caused by deposition of the tri-metallic strip beam over a sharp edge of  $\text{SiO}_2$  gap spacer layer. This sharp edge could cause the beams to warp, resulting in larger than desired beam gap. Adjusting the etching of the  $\text{SiO}_2$  to remove the sharp corners before metal deposition could reduce the stress concentrations in this area.

Packaged devices from the initial wafer lots were tested in a laboratory centrifuge so that closure contact and resistance could be determined. The beams failed to make switch contact at the target acceleration or even at three times the target acceleration. This failure to make electrical contact was due either to an excessive beam gap underneath the cantilever structure, combined with the enhanced stiffness of the beam, or to the presence of nonconductive material in the contact area of the switch.

Another phenomenon was that switches that were measured to be electrically shorted (closed) failed to open under high reverse acceleration. These closed switches may have been mechanically bent in wafer-handling procedures or during die separation, or cold welding may have occurred between the gold surfaces on the beam and underlying contact pad.

## 4. Conclusions

We have demonstrated a fabrication procedure for producing micromechanical multilevel metal cantilever beam switch arrays using semiconductor process technology. These beams could be produced in large quantities at a low cost. Problems with wafer-handling procedures, adequate residual removal, die separation procedures, and gold-to-gold cold welding contributed to statistically low yields and nonfunctioning switches. Studies on other beam materials, such as silicon, could be performed with the goal of creating more rigid beams with larger restoring forces and heavier end masses. Studies in electrical contact materials, such as evaporated platinum film, for the fixed side of the beam contact could correct the cold welding problem.

## Acknowledgments

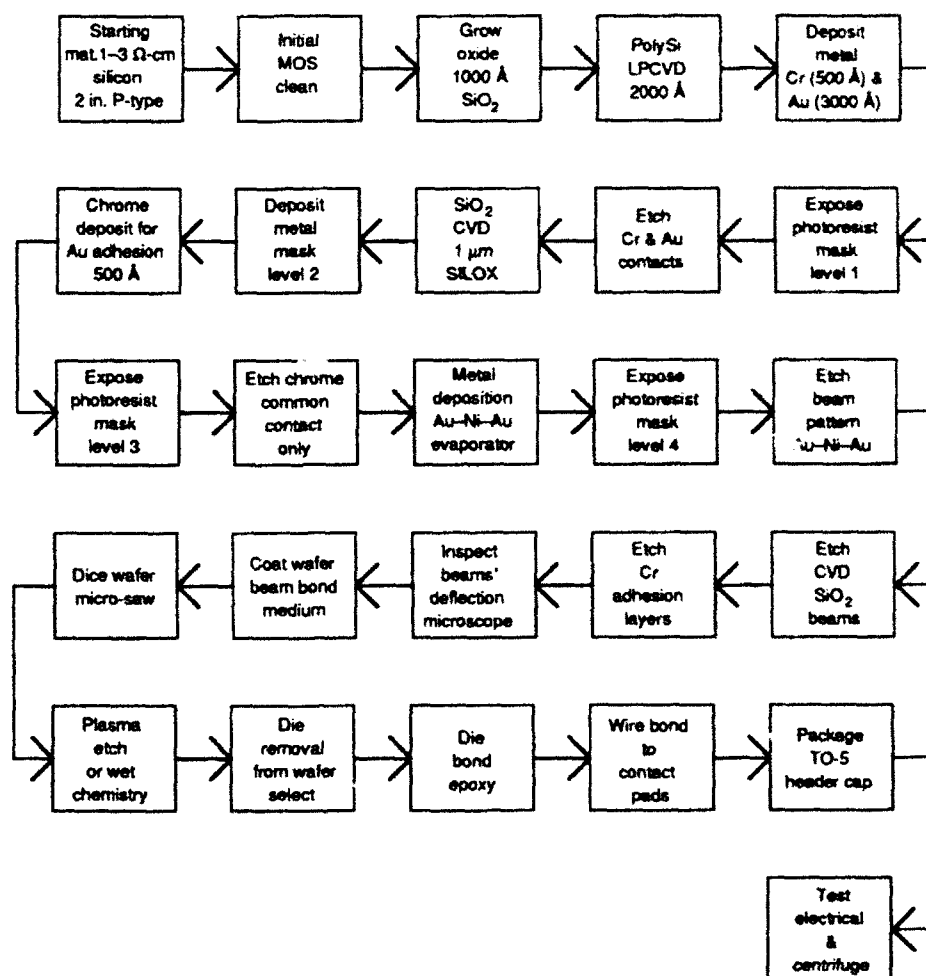
The authors wish to acknowledge Theodore Blomquist's leadership and efforts in the design and fabrication of the micromechanical cantilever beam switches. We also wish to acknowledge the support of Robert B. Reams for his assistance towards the original design concepts used during the development of the photomasks used for the cantilever beam structure, and Judith McCullen for her help in the photolithography and wafer processing of the cantilever beams. Also, the authors wish to acknowledge the valuable support given by David Overman, Charles Robinson, and Robert Warner.

## **Appendix A. Description of Cantilever Beam Design**

To facilitate the cantilever beam process development work, we chose a design based on work done by Westinghouse researchers in 1972,<sup>1</sup> in which they developed a similar device using electroplated gold to build the cantilever beams. Although the beam lengths and widths used in our work are similar to those in the Westinghouse designs, the beam metallurgy and thicknesses are different. It was not within the scope of this work to attempt a detailed analysis of the structures to determine the actual closing forces that could be expected. Our focus was on developing a procedure to demonstrate that these types of beams could be successfully fabricated in a manner compatible with commercial integrated circuit processing.

The actual beam design used for our work is shown in figure 4 in the main body of the report. The three different beam lengths are used to give three different closing accelerations. As shown in the fabrication flow diagram (see fig. A-1), the beam is composed of a gold-nickel-gold sandwich that is  $1.9\text{ }\mu\text{m}$  thick and  $50.8\text{ }\mu\text{m}$  wide, in lengths of 228.6, 177.8, and  $101.6\text{ }\mu\text{m}$  each, with a contact gap of  $1\text{ }\mu\text{m}$ .

**Figure A-1. Flow diagram for cantilever beam fabrication process.**



<sup>1</sup>W.D. Frobenis, S. A. Zeitman, M. H. White, D. D. O'Sullivan, and R. G. Hamel, *Microminiature Ganged Threshold Accelerometers Compatible with Integrated Circuit Technology*, IEEE Trans. Electron Devices ED-19, No. 1 (January 1972).

## **Appendix B. Chemistry and Materials Used in Cantilever Beam Process**

## B-1. Chemical Solutions

### B-1.1 *MOS Clean*

The MOS (metal oxide semiconductor) cleaning process consists of three cleaning and rinsing steps.

- Solution of 5 parts Di (deionized)  $H_2O$  to 1 part  $NH_4OH$  to 1 part  $H_2O_2$ ; immerse for 20 min at  $80^\circ C$ ; rinse in  $DiH_2O$
- 1 part  $DiH_2O$  to 50 parts HF; immerse for 10 s; rinse in  $DiH_2O$
- 6 parts  $DiH_2O$  to 1 part HCL to 1 part  $H_2O_2$ ; immerse for 15 min at  $80^\circ C$ ; rinse in  $DiH_2O$

### B-1.2 *Gold and Nickel Etch*

The gold etch solution diluted from full strength yields better control of metal beam line edges.

Solution: 400 gm KI potassium iodide, 100 gm  $I_2$  iodine, and 400 ml  $H_2O$   
Etch rate: 400 to 1600 nm/min

### B-1.3 *Chrome Etch*

Solution: 9 parts saturated ceric sulfate solution to 1 part  $HNO_3$   
Etch rate: 80 nm/min

### B-1.4 *$SiO_2$ Chemical Vapor Deposited (CVD) Oxide (Buffered HF)*

Solution: 10 parts  $NH_4F$  to 1 part 48-percent HF

Etch rate: ~65 to 75 nm/min for thermal silicon dioxide, ~180 to 220 nm/min for ambient pressure CVD oxide

### B-1.5 *Polysilicon Etch*

Solution: 100 ml  $DiH_2O$ , 250 ml  $HNO_3$ , and 4 ml HF  
Etch rate: 310 nm/min (undoped polysilicon)

## B-2. Materials

The following materials are needed for the cantilever beam process.

Photoresist:	KT1 757 negative photoresist
Chemical etches:	stored in plastic polyethylene containers
Dishes:	Teflon (Petri type)
Tweezers:	flat-tipped stainless steel
Water rinses:	$DiH_2O$ , 18 M $\Omega$ -cm resistivity
Gold:	99.999-percent pure gold 0.1016-cm-diameter wire
Chrome:	99.999-percent pellet form
Nickel:	Grade A sheet 0.00254 cm thick
Evaporator filaments:	Tungsten coils

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